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Semiconductor Measurement Technology:

A Wafer Chuck for Use Between −196 and 350°C

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R. Y. Koyama and M. G. Buehler

Electron Devices Division
Center for Electronics and Electrical Engineering
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

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PREFACE

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A WAFER CHUCK FOR USE BETWEEN -196 and 350°C

R. Y. Koyama and M. G. Buehler
Electron Devices Division
National Bureau of Standards
Washington, DC 20234

ABSTRACT

This report describes the design and characterization of a variable-temperature wafer apparatus for use in the detection of electrically active defects which produce deep levels in the band gap of silicon. In its present form, the wafer chuck can heat and cool wafers as large as 51 mm in diameter over the temperature range from -196 to 350°C; heating rates as high as 7°C/s have been achieved. The uniformity of the temperature across the chuck under static conditions is estimated to be better than ±0.4°C. Construction details of the chuck are given in an appendix. The use of this apparatus is illustrated by wafer mapping the gold defect density in diodes fabricated across a silicon wafer.

Key Words: Deep level measurements; defect mapping; hot/cold wafer chuck; thermal wafer chuck; thermally stimulated measurements; wafer chuck, variable temperature.

INTRODUCTION

The detection of electrically active defects which produce deep levels in the band gap of semiconductors is an important aspect of material and device characterization in the semiconductor industry. Techniques such as transient capacitance and current measurements [1], thermally stimulated current and capacitance measurements (TSM) [2], and deep level transient spectroscopy (DLTS) [3] are extremely sensitive and useful for establishing energy levels, emission rates, and densities of deep level defects. These techniques depend on the manipulation of the specimen temperature during some portion of the measurement; typically, temperatures in the range from -196 to as high as 300°C are required, depending on the semiconductor band gap energy.

Traditionally, deep level measurements have been performed in cryostats on test devices which have been scribed from wafers and individually packaged [2]. Great advantage could be derived by the ability to perform these deep level measurements on devices which can be probed in wafer form. This would eliminate operations such as scribing, dicing, die bonding, wire bonding, and pack-

age sealing in the processing, and shorten the time from wafer completion to deep level test measurements. Because the wafer stays intact, variations of parameters such as defect density and electrical device characteristics across the wafer could easily be determined. In addition to being a useful research tool in the laboratory, the wafer handling capability would allow these measurements to be used as a routine production diagnostic tool. The use of these techniques at intermediate points in the processing of wafers to determine the effect of particular processing steps on the activation or introduction of defect centers has particular application in the processing of power devices [4] and solar cell devices in which the lifetime of minority carriers is an especially important concern.

In this paper, a variable-temperature wafer apparatus capable of performing deep level* measurements on wafers is described. By using liquid nitrogen as the coolant, the apparatus covers the temperature range between -196 to over 350°C with heating rates as high as 7°C/s. Sensitivity for electrical measurements is sufficient to allow current measurements as low as 0.2 pA or capacitance changes (1 MHz) as small as 5 fF.

THE VARIABLE-TEMPERATURE WAFER CHUCK

The thermal and electrical requirements of deep level measurements led to the design and construction of the thermal chuck shown in figure 1. It shows an isometric view of the component parts of the chuck with the various parts identified. A nickel-plated copper top plate (3) has vacuum grooves for holding the test wafer in place, a hole for thermocouple insertion, and mounting holes for a wafer index-stop (2). This top plate is isolated from the chuck body (5) by an insulator plate (4) which must provide good electrical isolation as well as good thermal conduction; a circular sapphire plate (0.25 mm thick by 67 mm in diameter) has been found to perform satisfactorily. The heart of the assembly is the chuck body (5) which is also fabricated from copper and plated with nickel. The chuck body consists of an integral cooling cavity and holes for four heater cartridges (10). An inverted view of this part with the heaters exposed is shown in figure 2. A stainless steel cover plate (6) encloses the cooling cavity and attaches to the manifold (9) for the coolant fluid. The 150-W heater cartridges (10) are silver soldered into the chuck body (5) which is subsequently heli-arc welded to the cover plate (6) and the stainless steel mounting ring (7). Since the mounting ring (7) is attached to supporting hardware, it has been designed with a thin rib (0.25 mm thick) on the circumference to minimize heat

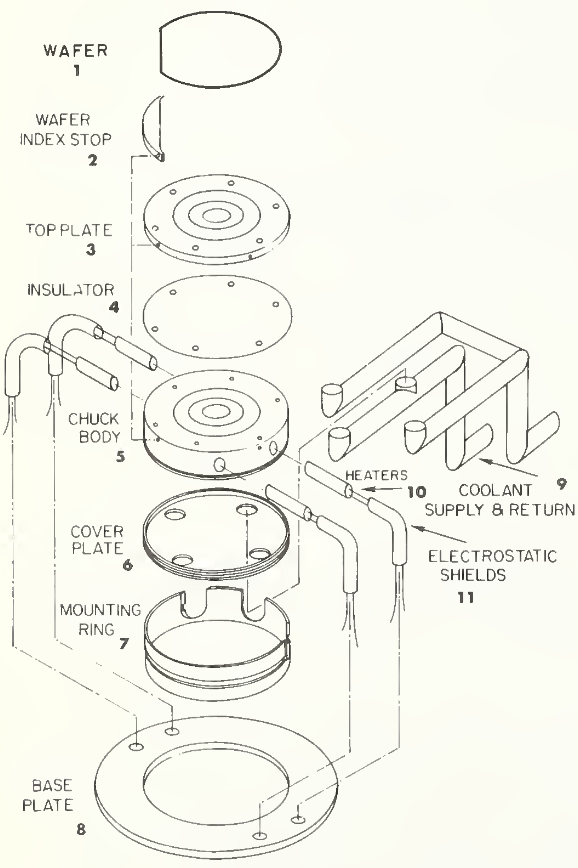

Figure 1. Isometric view of the major thermal chuck components.

* This apparatus would also be useful and has been used for bias-temperature stress (BTS) measurements on metal-insulator-semiconductor (MIS) structures. BTS measurements with thermal stress of 300°C have been utilized to detect mobile ion contamination in silicon dioxide MIS capacitors.

transfer to the support; this is necessary in order to minimize mechanical motion of the chuck due to differential thermal expansion and contraction of the support hardware. The power leads for the heater cartridges are shielded along their entire length with either solid (11) or flexible metal shields (not shown). The top surface of the chuck body (5) is identical (including vacuum grooves) to the top plate (3); for measurements which do not require electrical isolation, this feature allows faster thermal response by mounting the wafer directly on the chuck body. Figure 3 shows a photograph of the assembled thermal chuck. The numbers are keyed to those in figure 1; in addition, the two thermocouples (12), the two chuck vacuum supply pipes (13) for wafer hold-down, and one pair of three sets of locking and leveling screws (14) are indicated. Each of the two type K [5] thermocouples has dual elements and is mounted to the chuck body and top plate by inserting it into holes drilled in the chuck body (5) or the top plate (3). To eliminate possible electrical interference, the thermocouple in the top plate is an isolated type.

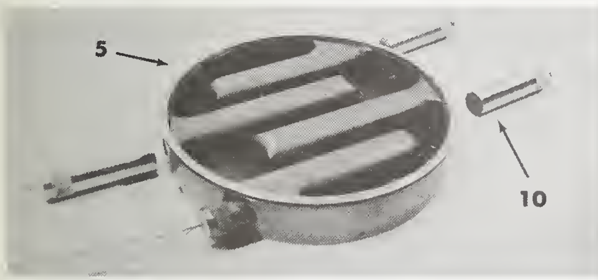

Figure 2. Inverted view of the chuck body with the four 150-W heater cartridges exposed (see fig. 1 for number key to components).

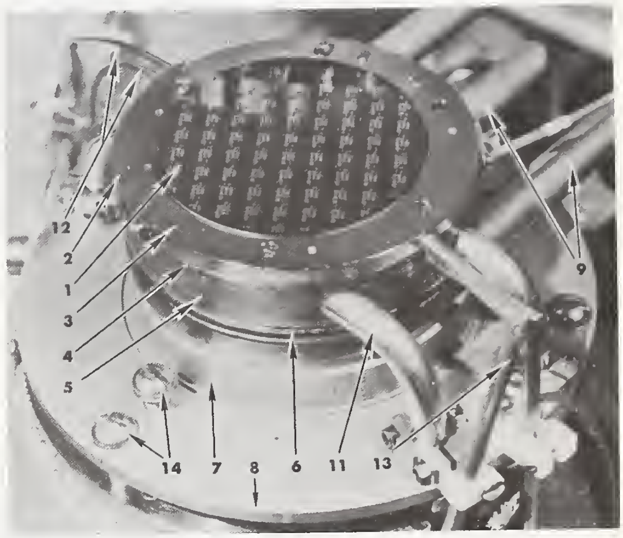

Figure 3. Photograph of the assembled thermal chuck (see fig. 1 and text for number key to components).

AUTOMATIC PROBING APPARATUS

To build in the capability for automation of measurements, the thermal chuck assembly was adapted to a modified automatic wafer prober (Teledyne - TAC, PR-100). This prober has a probe-ring assembly which can accommodate as many as 60 individually adjustable probes. Once mounted and adjusted, the probes remain fixed. Automatic probing is accomplished by moving the chuck-mounted wafer to the appropriate position relative to the probes. Movement in the x-y plane is accomplished by a table on which the chuck is mounted; after reaching the desired position, a small vertical motion (z) raises the chuck to make contact between the wafer and the measurement probes. After initial alignment of first the wafer to the prober axes and then the measurement probes to the contact pad geometry, the prober can automatically index the wafer from die to die at a preset index interval. In addition, a computer interface is utilized to control and execute a variety of electrical parameter measurements of devices fabricated on the wafer.

The low temperature requirements of the deep level measurements dictate the use of a cryogenic fluid for the thermal chuck coolant. Since it is important to maintain a low relative humidity to minimize or eliminate the condensation of water vapor on the wafer at low temperatures, the thermal chuck and the wafer prober were enclosed in a sealed box. The enclosure is continuously purged ($\sim$2.5 L/min) with dry nitrogen.

The main features of the box are shown in figures 4, 5, 6, and 7. (Refer to table 1

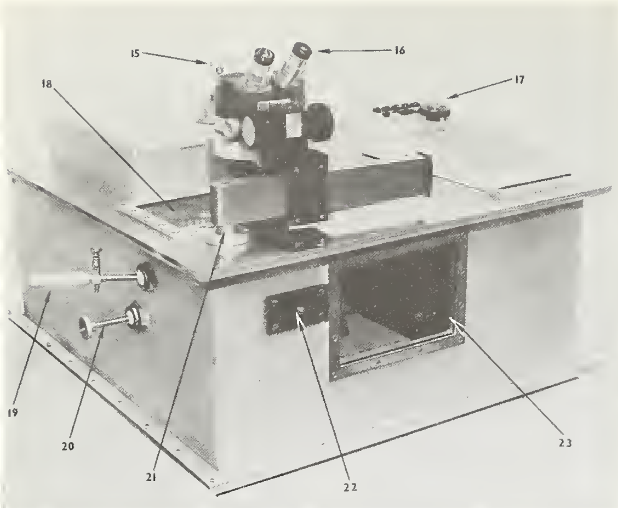

Figure 4. Front view of the box enclosing the automatic wafer prober (see table 1 for number key to components).

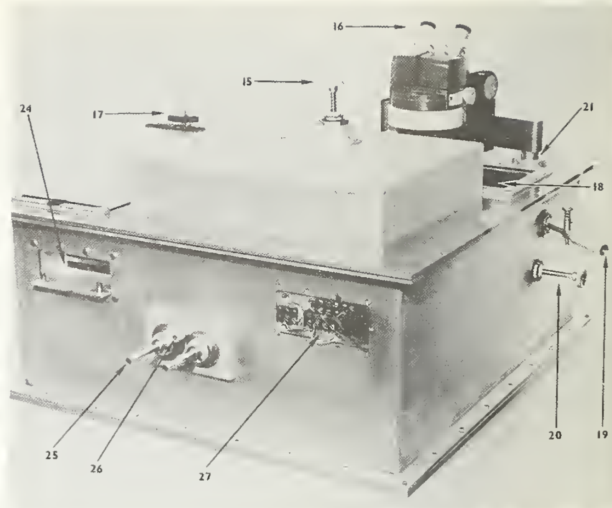

Figure 5. Back view of the box enclosing the automatic wafer prober (see table 1 for number key to components).

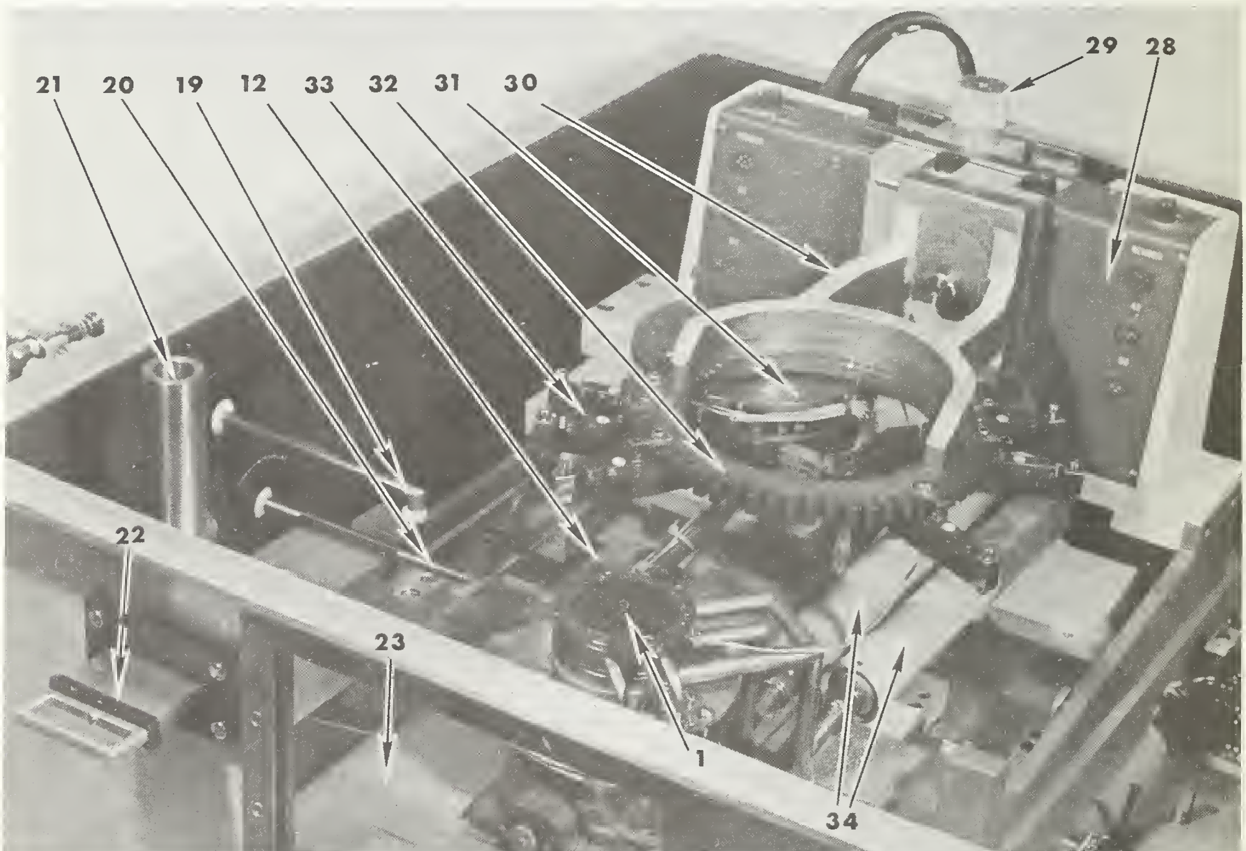

Figure 6. Inside view of the box with the top cover removed (see table 1 for number key to components and figs. 1-3 for details of the thermal chuck).

Table 1. List of the Major Components.

A. Thermal chuck components

1. 51-mm diameter wafer
2. Wafer index stop (stainless steel)
3. Top plate (nickel-plated copper)
4. Insulator plate (0.25-mm by 67-mm diameter sapphire)
5. Chuck body (nickel-plated copper)
6. Cover plate (stainless steel)
7. Mounting ring (stainless steel)
8. Base plate (stainless steel)
9. Coolant manifold (2 each, stainless steel)
10. Heater cartridge (4 each)
11. Electrostatic shields (4 each, stainless steel)
12. Thermocouple (2 each)
13. Chuck vacuum supply (2 each)
14. Leveling and locking screws (3 pairs)

B. Prober and enclosure components

15. Probe ring height manipulator
16. Stereo microscope
17. Prober control panel
18. Top viewport
19. Wafer transfer probe
20. Wafer θ-alignment manipulator
21. Microscope mounting post
22. Wafer transfer slide
23. Front viewport
24. Prober control connector
25. Liquid nitrogen feed-throughs (2 each)
26. Dry nitrogen feed-throughs (2 each)
27. Heater power, thermocouples, etc.
28. Prober bridge assembly
29. Probe ring height micrometer
30. Probe ring support
31. Multiprobe assembly
32. Probe ring
33. Probe and manipulator (6 each)
34. Telescoping tubes/stainless steel bellows (1 pair)

C. Instrumentation

35. Digital voltmeter
36. Voltage source
37. Capacitance meter
38. Electrometer

for the numerical listing of the components.) All sealing surfaces utilize gaskets or "O" rings. Utilities are interfaced at the back of the box; these include the prober control (24), liquid nitrogen feed-throughs (25), dry nitrogen feed-throughs (26), heater power, and thermocouples (27). Figure 6 shows an inside view of the prober box. The thermal chuck assembly is seen in the foreground. In operation, a wafer is loaded into the box by the wafer transfer slide (22); once inside the box, the wafer is picked up with the vacuum-operated wafer transfer probe (19) and placed on the surface of the thermal chuck. Specimen wafers can be changed in a matter of seconds without having to open the box; the wafer slide assembly (22) which is sealed to the box in both the fully open and fully closed positions, minimizes penetration of room air into the box. (Additional details of the chuck and the wafer slide mechanism are given in Appendix A.) Wafer alignment to the prober axis is accomplished by rotating the chuck assembly about an axis perpendicular to its center with the θ-manipulator (20); this is done while viewing the wafer with the microscope (16) through the top viewport (18). The bridge structure (28), which supports the probe ring (32), is shown displaced toward the rear for clarity; the probe ring is normally in the region above the thermal chuck. Mounted on the probe ring (32) are six individually adjustable probe manipulators (33), and a 6 by 6 multiprobe array (31). The multiprobe is a fixed array of 36 individually biasable probes which can be used for simultaneous probing of 36 devices spaced at the appropriate interval on the wafer; this multiprobe is usable to at least 300°C.* Neither the individual probes (33) nor the multiprobe array (31) is externally adjustable or accessible after the box is

* The multiprobe array was designed to allow BTS on 36 devices simultaneously during one thermal cycle of the chuck.

closed. However, fine adjustment on the probe contact pressure is available with the height micrometer (29) which is accessible externally through the probe ring height manipulator (15). Under measurement conditions, the top and front viewports (18, 23) are covered to prevent light from entering the box. The x, y, and z positions of the thermal chuck are controlled externally from the control panel (17). Figure 7 shows a view of the prober box along with its associated complement of commercially available instrumentation for the TSM technique.

Liquid nitrogen is circulated to the movable chuck from the feed-throughs (25) at the back of the box through a pair of stainless steel welded bellows. Except for extension and compression, these bellows are confined within a pair of telescoping tubes (34) to minimize vibrational motion of the bellows caused by expansion of the liquid nitrogen. These tubes also serve to insulate the metal bellows from the box ambient. Excessive cooling of the box ambient, and eventual cooling of the prober mechanism under prolonged liquid nitrogen use was found to cause mechanical malfunction of the x-y translation mechanism.

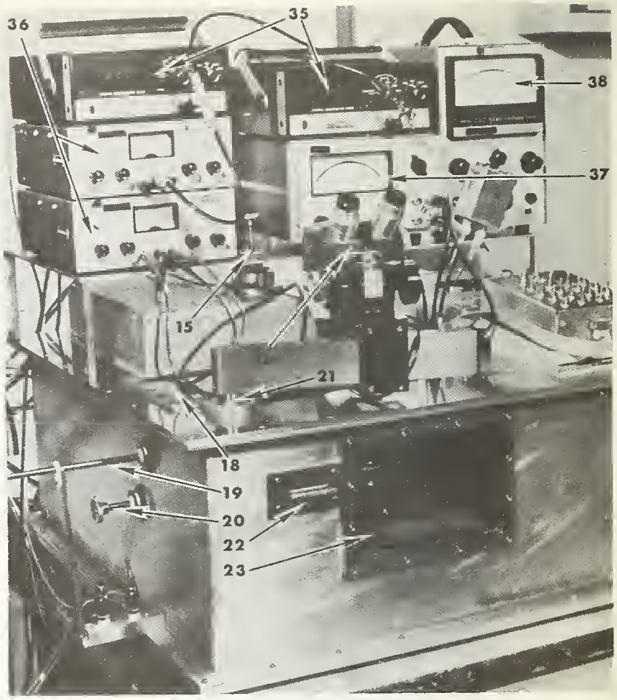

Figure 7. Typical experimental setup with instrumentation (see table 1 for number key to components).

THERMOMETRY

In order to realize useful information from any variable-temperature measurement system, appropriate attention must be given to the thermometry. In this case, there are two aspects: (1) measurement of the actual wafer or device temperature and (2) the uniformity of the chuck temperature. Each of these aspects needs to be considered under both static (isothermal) and dynamic conditions of the chuck. In addition, for dynamic temperature measurements, the heating rate must be established. The importance of each particular aspect depends on the measurement that is being made. For example, in order to measure the energy level of an unknown deep level defect, it is necessary to know the specimen temperature accurately when using the DLTS [3] technique; for TSM [2], one needs to know both the temperature and the heating rate. On the other hand, when the objective is to simply measure the density of a deep level defect by the thermally stimulated capacitance technique, an accurate knowledge of the temperature or heating rate is not required.

The temperature of the top plate is monitored by an isolated thermocouple which is inserted into a hole from the side. The temperature-sensitive junction is positioned at the center. The thermocouple itself was checked for absolute calibration at -195.66°C [6], and a measurement of the thermocouple output voltage against temperature over the range from -196 to 20°C confirmed that its characteristics conformed to published thermocouple calibration charts [5].

Figure 8 shows a set of typical heating and cooling cycles for two different measurement sequences (the temperatures were measured with the thermocouple in the top plate). The upper curve represents heating from room temperature to over 300°C and back to room tem-

perature.* Heating to 300°C requires about 70 s and cooling back to room temperature requires less than 2 min. The lower curve represents a temperature cycle required for TSM. Cooling to liquid nitrogen temperature is accomplished in less than 4 min. The increase in cooling rate just prior to reaching -196°C is due to the complete filling of the chuck with liquid nitrogen. Heating back to room temperature requires about 45 s. (Although TSM of mid-gap defects in silicon are completed at room temperature, higher band gap materials may require heating above room temperature.) Figure 9 shows a detailed heating curve and a heating rate curve from liquid nitrogen temperature. This typical heating curve was obtained with approximately 75 percent of full power applied to the chuck heaters. Although high heating rates are required for good signal-to-noise ratios in TSM, the nonlinearity of the heating rate is of no consequence [2] as long as the rate at the emission temperature is known. With this apparatus, heating rates as high as 7°C/s can be obtained.

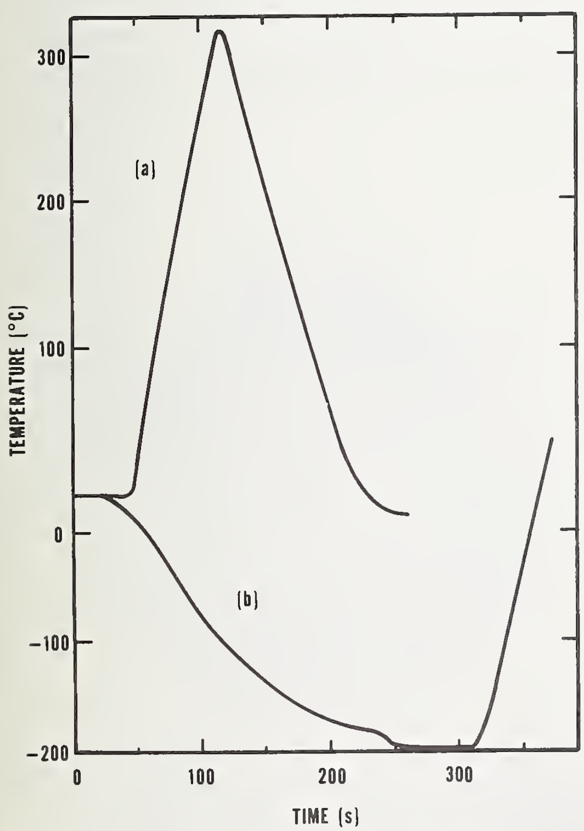

Figure 8. Typical heating and cooling response curves for the chuck: a) above room temperature, and b) below room temperature (typical for TSM).

Under dynamic conditions as illustrated in figures 8 and 9, the indicated thermocouple temperature and the actual chuck/wafer temperature can be significantly different. Because the thermocouple junction is isolated from the chuck top plate, it has a thermal time constant approaching several hundred milliseconds. During a typical TSM scan (heating from -196 to 23°C) the device temperature is higher than the thermocouple indicates. Temperature calibration for a TSM scan is accomplished by calibrating the forward voltage drop of a junction diode (fabricated on the wafer) against the thermocouple temperature under static isothermal conditions (assuming that there is no temperature gradient between the fabricated junction and the thermocouple). Under dynamic conditions, the diode response is much faster than the thermocouple; thus, the measured forward voltage drop of the diode gives the actual device temperature.

The nonuniformity of the chuck temperature under "isothermal" conditions was determined by measuring the variation of the forward voltage drop, V_F, of an array of gold-diffused n^+p diodes spaced at 2.54-mm intervals on a 51-mm diameter wafer [7]. Static temperature conditions were maintained at the center of the chuck by a temperature control

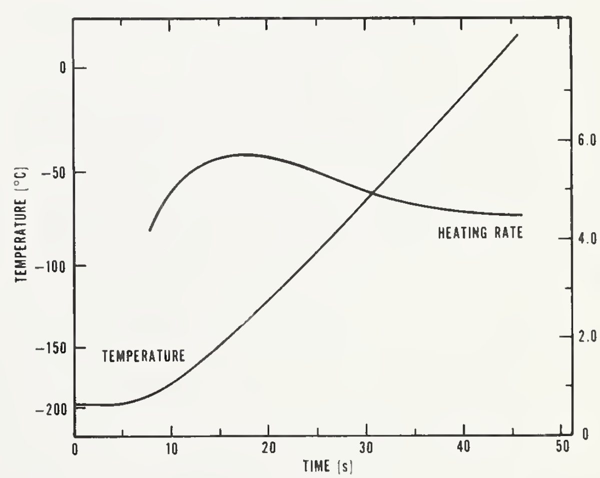

Figure 9. Typical temperature and heating rate curves for a thermally stimulated measurement with approximately 75 percent of full power applied to the heaters.

* This cycle would be typical of that used for a BTS test, except that the stress period at 300°C was omitted. It should also be noted that the actual temperature during BTS is an important parameter and should be accurately known.

system which monitored the thermocouple output. At a given temperature set point, the control system provides enough heating power to balance the cooling input from the liquid nitrogen. Under these conditions, the uncertainty of the set point temperature was about ±0.1°C. The forward voltage drop of the diode array (at a fixed forward current) was recorded as a function of wafer position for a sequence of temperatures between liquid nitrogen temperature and 50°C. The measured variation of the voltage drop with position is due to both the inherent differences of the diodes as a result of their fabrication and the possible nonuniformity of the chuck temperature.

The forward voltage characteristic for a single device near the center of the wafer is shown in figure 10. The measurements were made with stationary temperatures at a forward current of 10 μA. There are two well-defined linear regions of the characteristic described by

$$V_{F1} = 0.415 - 2.77 \times 10^{-3}T \qquad (1)$$
$$-196°C \le T < -40°C$$

$$V_{F2} = 0.432 - 2.12 \times 10^{-3}T \qquad (2)$$
$$-10°C < T \le 35°C$$

where T is the temperature in °C; Pearson's correlation coefficients for V_{F1} and V_{F2} are 0.99996 and 0.99991, respectively. As explained by Sclar and Pollack [8], an extrapolation of V_{F1} to absolute zero (-273°C) gives V_{F1} (-273°C) = 1.171 V which corresponds to the intrinsic band gap of silicon at -273°C. If all devices on the wafer had identical forward voltage characteristics, temperature profiling would simply be accomplished by measuring the voltage drop as a function of wafer position. Unfortunately, due to the nonuniformity of the gold diffusion process in the fabrication of the wafer, each device has a unique slope; however, all characteristics intersect V_F = 1.171 V at -273°C. Figure 11 is a map of the forward voltage drop at 24°C of approximately 300 devices spaced at 2.54-mm intervals on the wafer. The total variation from light regions to dark regions is 0.3664 to 0.4091 V, respectively. Rotation of the wafer on the chuck causes rotation of the pattern indicating that the image is due to the wafer and not the chuck. In fact, at 24°C, it is fair to assume that the chuck is in equilibrium with its surroundings (no heater power or cooling applied) and thus that a true isothermal condition exists.

For the purpose of this temperature nonuniformity determination, high and low outliers were removed from the array (not measured) and only a select group consisting of 170 devices with fairly uniform characteristics was measured. At each temperature, "isothermal" conditions were established by the controller and the 170 devices were probed to measure the forward voltage drop. The data points (a) of figure 12 show the measured difference

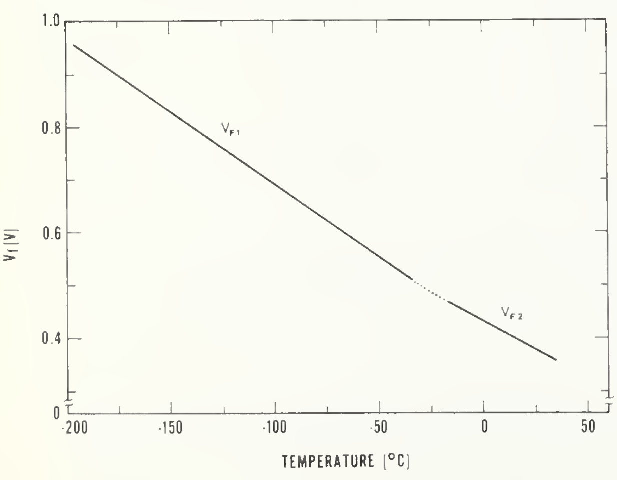

Figure 10. Forward voltage drop characteristic for a specific n^+p gold-diffused diode.

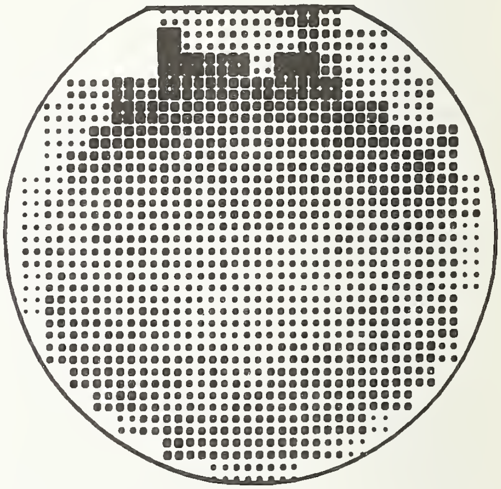

Figure 11. Wafer map of the forward voltage drop of the n^+p diodes. Approximately 300 data points are plotted with the dark-to-light shading representing a forward voltage variation from 0.4091 to 0.3664 V, respectively. (A quadrant of four squares represents one data point.)

$$\Delta V_M = V_{Fmax} - V_{Fmin} ,$$

where V_{Fmax} and V_{Fmin} are, respectively, the largest and smallest forward voltage drop of the measured group at each temperature. The spread in the measured voltage drops ranges from 2.5 mV at liquid nitrogen temperature (-196°C) to 11.5 mV at 58°C. The vertical height of each data point represents the measurement uncertainty as determined from several measurements at each temperature. The measured spread, ΔV_M, is due to two contributions: (1) the "natural" spread of voltages (ΔV_D) as a result of nonuniformity of device characteristics, and (2) the nonuniformity of the local wafer temperature (ΔT), resulting in a deviation of ΔV_M from ΔV_D.

The line labeled (b) in figure 12 represents an estimate of the temperature dependence of the natural spread, ΔV_D. It was established by drawing a straight line through the room temperature data point (24°C) and the point $\Delta V = 0$ at -273°C. The reasonable assumption that the chuck is isothermal at 24°C means that the measured spread is due only to the natural variations in the individual devices. In addition, since all devices have an extrapolated forward voltage drop of 1.171 V at absolute zero (-273°C) [8], then the natural spread, ΔV_D (-273°C) = 0. Hence, the two points on the line ΔV_D are fixed; the assumption of linearity is justified in Appendix B.

In the region above -20°C, the data points of the measured spread essentially follow the straight line of the natural spread; this suggests that there is no contribution to the measured spread from nonuniformities of the chuck temperature. The largest deviations between the measured spread and the natural spread occur between -160 and -30°C. Assuming that this deviation is due only to variations in the chuck temperature, and that the measured spread is the sum of the two independent contributions (i.e., ΔV_M =

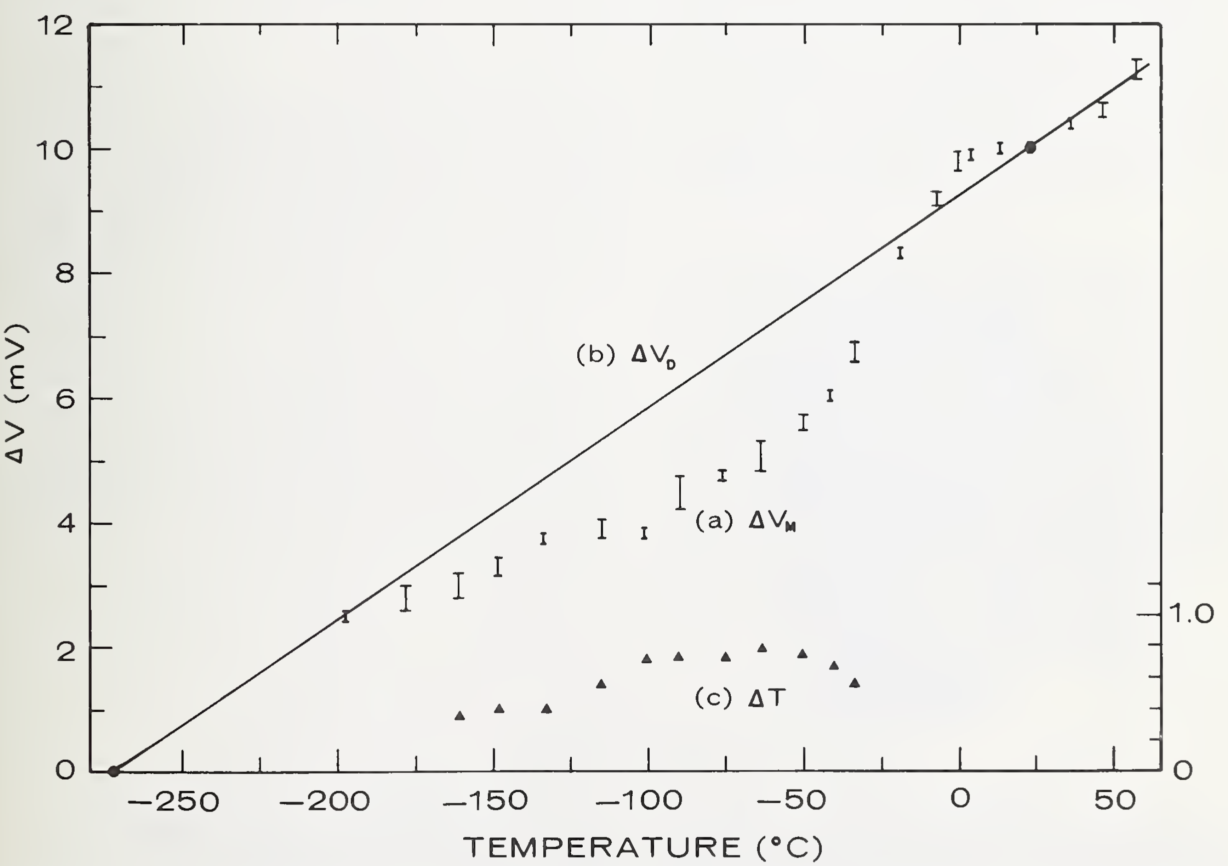

Figure 12. Curves representing: a) the spread of the forward voltage drop of a selected group of 170 diodes as a function of temperature, b) a linear plot representing the "natural" spread of the forward voltage drop due to device variations, and c) the deduced spatial variation of the chuck temperature as a function of the temperature.

$\Delta V_D + \Delta V_T$, where ΔV_T is the contribution due to variations in the chuck temperature uniformity), then the nonuniformity of the chuck temperature can be calculated. This is shown plotted in figure 12 as curve (c) and was determined from the difference between ΔV_M and ΔV_D, divided by the slope of a typical diode characteristic given in eq (1). The largest deviation is about 0.8°C near -65°C, resulting in an uncertainty of ±0.4°C at a given temperature set point. Where this uncertainty is critical, it would be necessary to make a specific calibration at the location of interest rather than rely on the indicated thermocouple temperature.

A curious consequence of these results is the fact that the measured spread, ΔV_M, can be smaller than the natural spread, ΔV_D. This is explained by the location of particular devices. In general, the shading of figure 11 reveals that the low voltage devices are near the center and the high voltage ones are near the edge of the wafer. Thus, a situation where the edge region is warmer than the center region would cause a decrease in the measured voltage spread. Intuition might suggest that the central region would be warmer than the edge due to the presence of the heaters. However, a study of the forward voltage wafer maps failed to reveal the "image" of the heaters and corroborates the interpretation given above.

A direct measure of the uniformity of the chuck temperature under dynamic conditions was not made. However, an indirect measure was obtained from the analysis of a series of TSM scans which were made as a function of wafer position under the same dynamic heating conditions. The location of the measured emission current peak or the depletion capacitance change in a junction diode caused by the discharge of a specific deep level defect is a function of both the heating rate and the temperature [2]. With the heating rate fixed at approximately 7°C/s by maintaining a constant heating power, any variations in the temperature at which the emission occurs can be interpreted as being due to variations in the chuck temperature with position. This analysis was performed at two different temperatures utilizing the gold donor level (which discharges at about -135°C) [9] and the gold acceptor level (which discharges at about -45°C) [9]. The results are represented in the two histograms of figure 13 which plot the number of devices on the wafer versus the temperature at which the emission occurs; the temperature was measured with the top-plate thermocouple and corrected for the heating rate lag. These results suggest that the variability of the chuck temperature with position under dynamic conditions is on the order of ±3°C. Where these variations are important to a measurement, it would be necessary to correct or account for them.

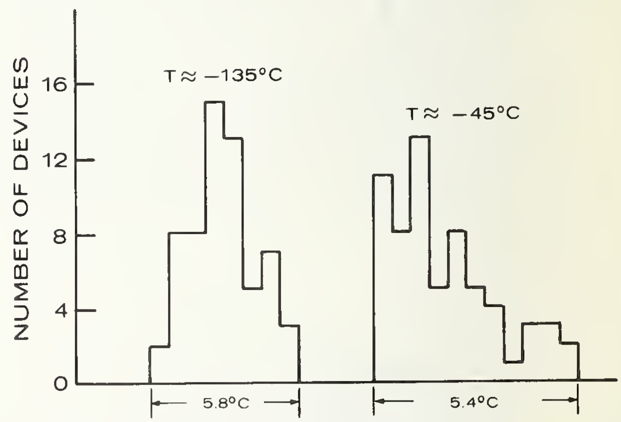

Figure 13. Histograms showing the variation of the temperature at which emission from the gold donor (-135°C) and the gold acceptor (-45°C) occurs; the nonuniformity of the chuck temperature under dynamic conditions of approximately 7°C/s is inferred from this variation.

DEFECT MAPPING

As an example of the use of this apparatus, a wafer map of the defect distribution across a gold-diffused silicon wafer was made. Thermally stimulated measurements were made on an array of n^+p gated diodes fabricated by a 2-μm phosphorus diffusion into <111>, 5 to 10 Ω·cm, p-type silicon wafers. The gold defect center was introduced by evaporating gold on the back surface of the wafer and diffusing at 825°C for 24 h. Figure 14 shows the thermally stimulated response from a typical diode on the processed wafer. The upper curve is the capacitance response and the lower is the current response. In each case,

the response was measured by first cooling the device to near liquid nitrogen temperature. Zero bias was applied to the diode to charge all defects with majority carriers (holes); a reverse bias of 15 V was then applied to form a depletion region. The current or capacitance was measured with the depletion bias maintained while the wafer was heated with a heating rate of about 7°C/s. At the appropriate temperature, the gold defect emits its trapped hole causing a measurable current, a slight collapse of the depletion region, and a measurable capacitance increase. In this example, the emission is due to the gold donor level located at 0.35 eV above the valence band [9]. The system noise in the x-y recorder tracings was approximately 2 fF and 0.1 pA for the capacitance and current, respectively.

The gold donor density was determined by measuring the thermally stimulated capacitance response as a function of wafer position. Following the work of Buehler [2], the defect density is given by

$$\frac{N_t}{N_A - N_D} \approx \frac{2(C_f - C_i)}{C_f} . \tag{3}$$

$N_t/(N_A - N_D)$ is the ratio of the defect density to the net background acceptor density; C_f and C_i are given in figure 14a. This expression is valid for the case when only one charge carrier is emitted, and $C_b^2 >> C_i^2$ where C_b is the zero bias diode capacitance. These conditions are satisfied here. Note that in this measurement, only the total charge flow as evidenced by the change in capacitance is important; the result is independent of the heating rate and also does not depend on an accurate knowledge of the temperature. An independent measure of the average acceptor density of the depletion region is required and was determined from a measurement of the capacitance-voltage characteristic of the same junction used for the TSM. The net acceptor density, $N_A - N_D$, was calculated from the standard Schottky relation:

$$N_A - N_D = \frac{2C_1^2 C_2^2 (V_2 - V_1)}{q\ \varepsilon_s (C_1^2 - C_2^2)} . \tag{4}$$

C_1, V_1 and C_2, V_2 are the capacitance-voltage pairs taken from the diode C-V characteristic; q is the electronic charge, and ε_s is the dielectric constant for silicon. The values of depletion capacitance were measured with V_1 = 5 V and V_2 = 15 V. These data were used to calculate the defect density from eq (3). Figure 15 displays the gold donor defect density as a function of position on the wafer. The darker areas represent regions of higher density, and the variation is from 2.34 to 3.61 × 10^{13} cm^{-3}. The system noise (2 fF) suggests that donor defect densities in the range of 1 × 10^{12} cm^{-3} would be detectable in this wafer.

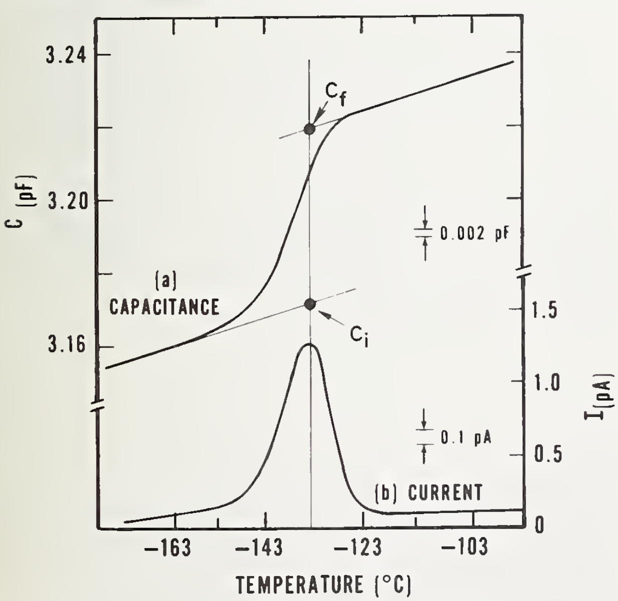

Figure 14. The thermally stimulated a) capacitance and b) current responses of a gold-diffused n^+p diode; the heating rate is about 7°C/s.

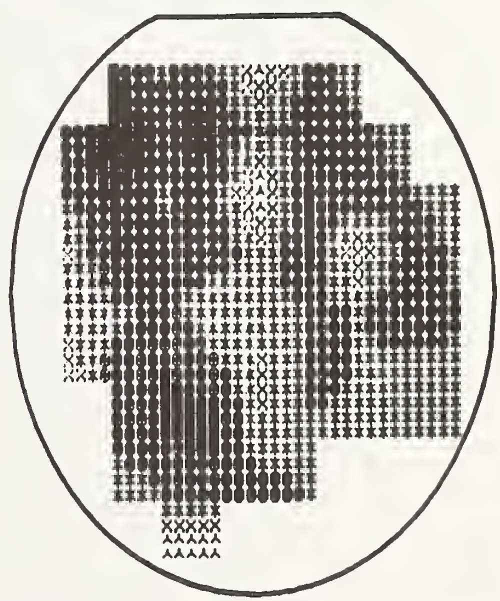

Figure 15. Wafer map of the gold donor defect density. The variation from light to dark regions is 2.3 to 3.6 × 10^{13} cm^{-3}. (Approximately 70 data points are plotted on a grid corresponding to the 5.08-mm spacing of the devices on the wafer. Shading at intermediate points is derived by interpolation.)

AUTOMATIC WAFER PROBING

A further aspect of this system which has not been discussed in detail is its utility as an automated wafer probing system. This feature in itself is similar to many commercial wafer probing systems; the unique feature of this system is that measurements under static temperature conditions can be made at any temperature in the range of -196 to 300°C.* For example, the wafer maps of forward voltage drop (e.g., fig. 11) for the temperature uniformity measurements were made under computer control at a series of temperatures from -196 to +58°C. The measurement of the data for the map at each temperature requires about 6 min. In addition, such device parameters as diode reverse leakage current [10], reverse recovery lifetime, and open circuit voltage decay lifetime have been mapped and have been seen to correlate with the measured defect density. This instrument can utilize the fact that most semiconductor properties are temperature dependent and provides a new dimension to measurements for diagnostics of fabricated wafers.

SUMMARY

A variable-temperature wafer chuck capable of excursions from -196 to 350°C has been designed, constructed, and evaluated. The chuck is part of an automatic wafer probing apparatus which is housed in a sealed enclosure to provide a dry environment. The apparatus can be used for a variety of measurement functions but was primarily designed for detection of deep levels in processed silicon wafers. As an example, the gold donor defect density in *p*-type silicon was mapped as a function of position on the wafer and graphically revealed the nonuniform defect distribution. The use of such apparatus as a diagnostic tool for monitoring defects during wafer fabrication should greatly enhance the process engineer's ability to control his process.

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* The automatic probing feature is employed only for measurements at static temperatures. Measurements requiring dynamic temperature excursions are performed manually on individual devices because small motions of the chuck (x, y, and particularly z) due to thermal expansion and contraction cause automatic probing to be unreliable.

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APPENDIX A

Mechanical Drawings for Parts

Given in figures A1 through A4 are the mechanical drawings for the basic components of the variable-temperature chuck and the wafer transport slide mechanism.

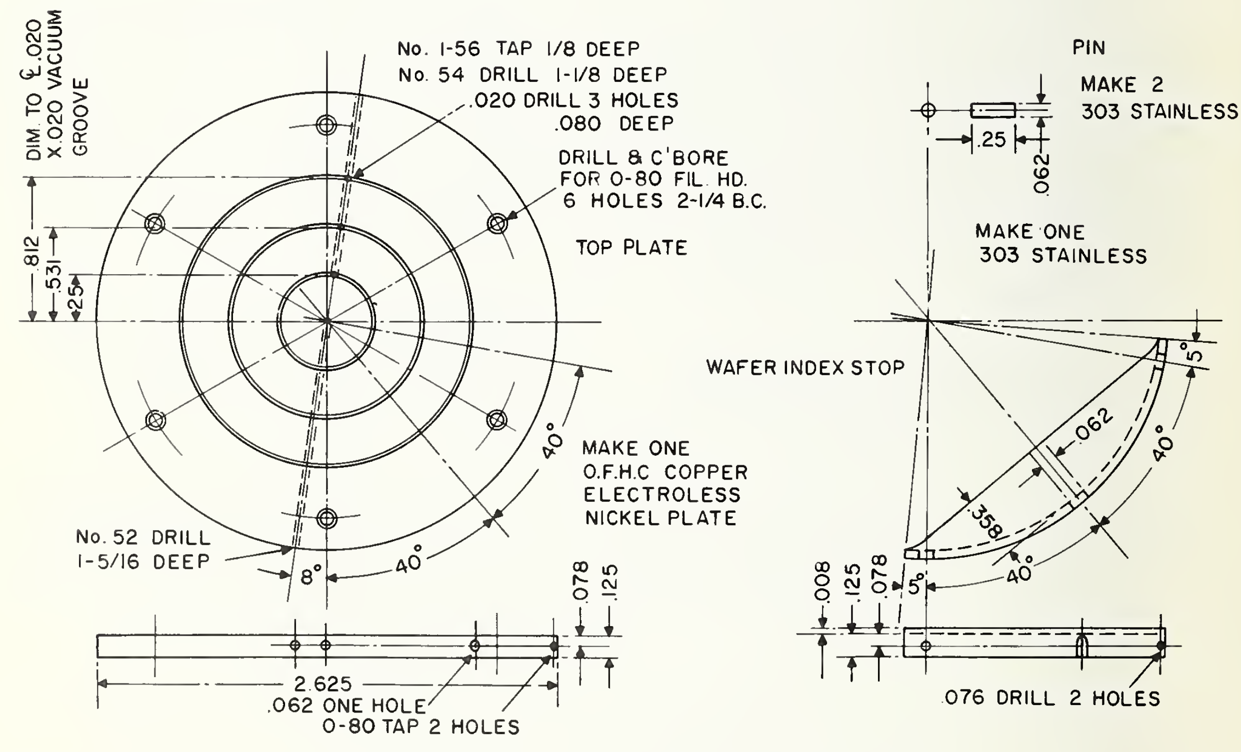

Figure A1. Mechanical drawings for the top plate, wafer index stop, and the index stop pin.

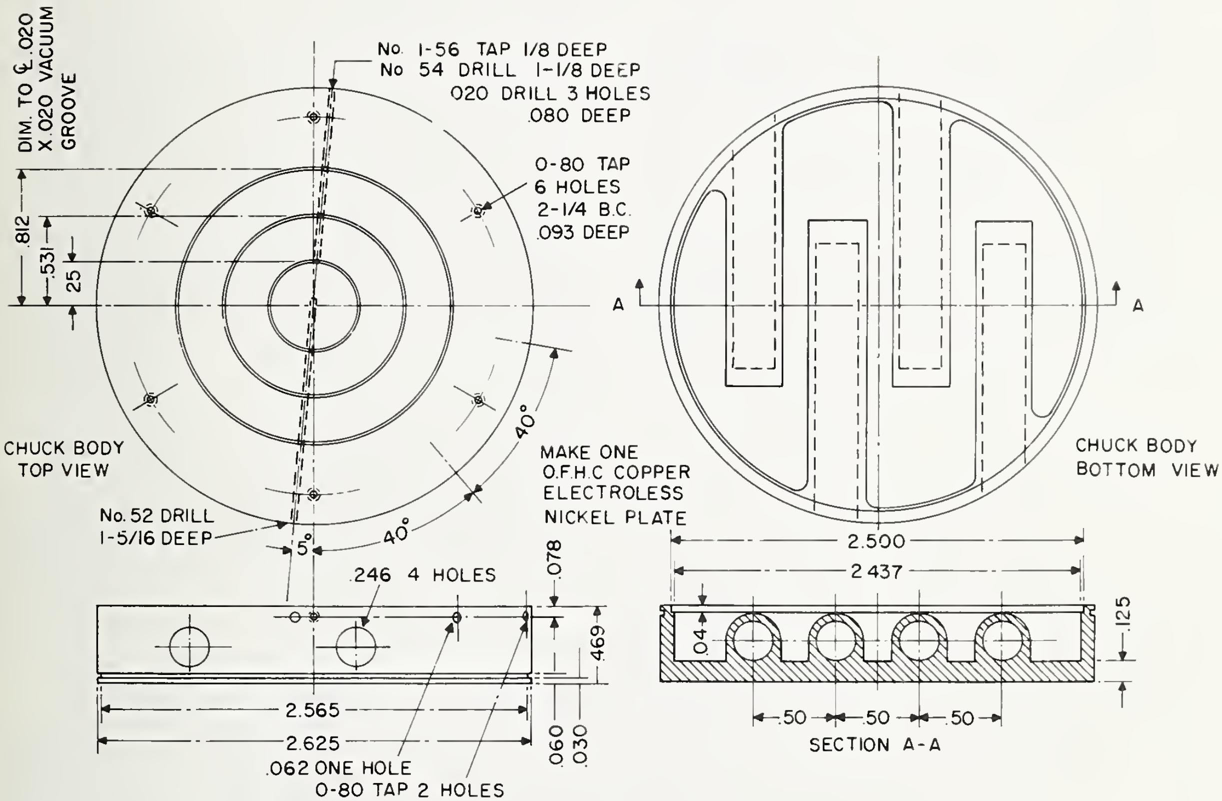

Figure A2. Mechanical drawing for the chuck body.

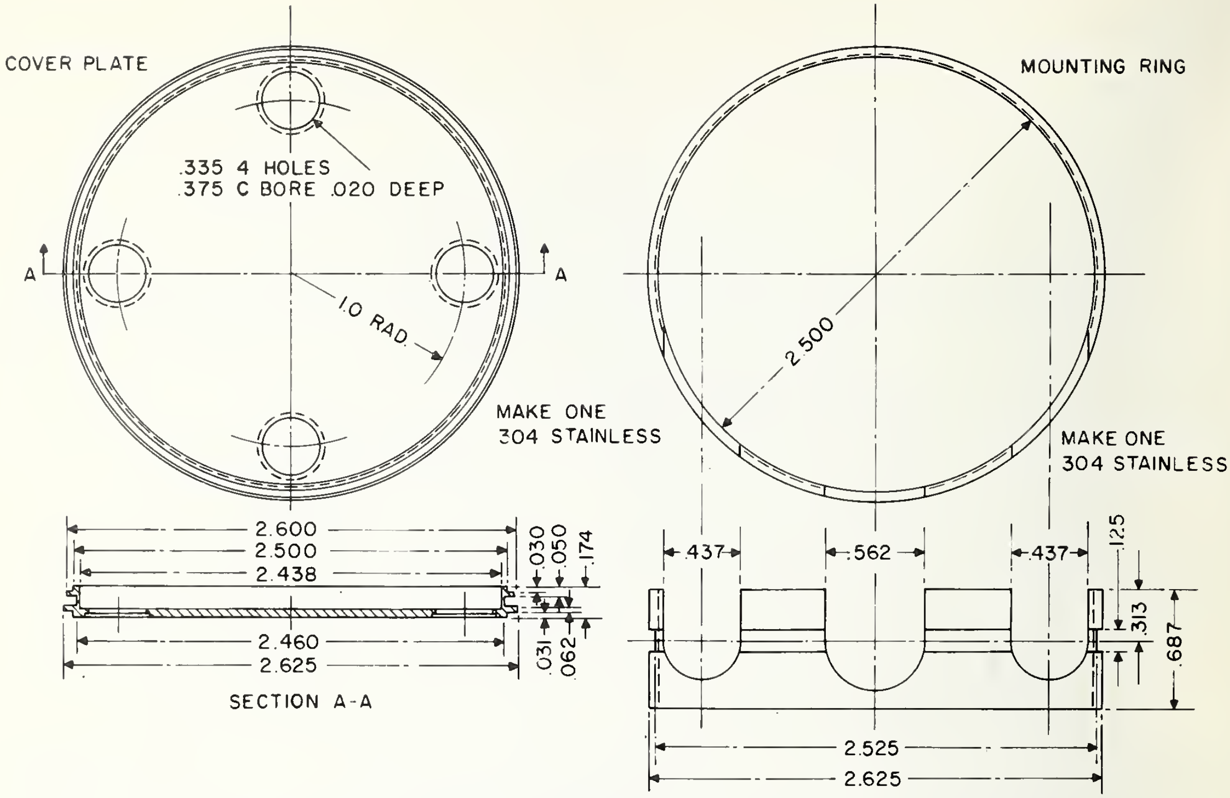

Figure A3. Mechanical drawings for the cover plate and mounting ring.

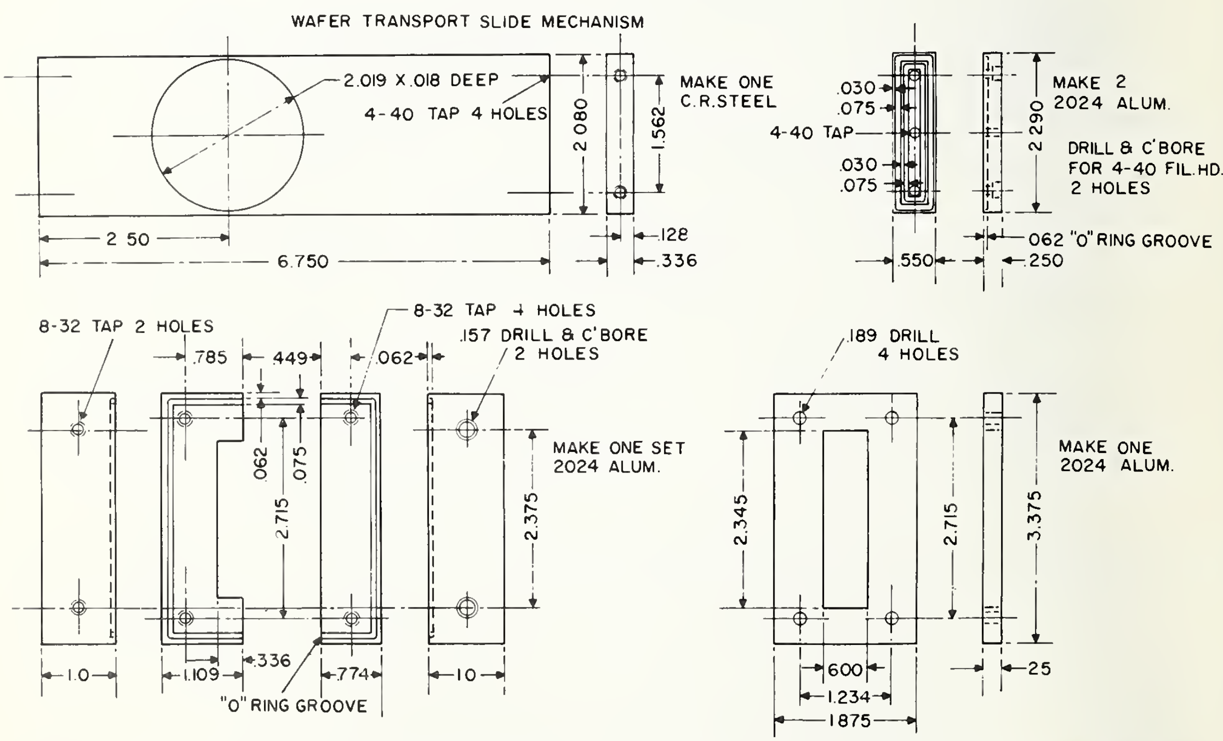

Figure A4. Mechanical drawings for components of the wafer transport slide mechanism.

APPENDIX B

The Linearity of ΔV_D

In the region below 40°C, assume a generalized form for eq (1):

$$V_F = A + BT \tag{B1}$$

where A and B are constants, and T is the temperature in °C. Two specific equations which represent the highest and lowest voltage devices of the group can, respectively, be written as:

$$V_{FH} = A_H + B_H T \tag{B2}$$

$$V_{FL} = A_L + B_L T \ . \tag{B3}$$

Hence, an equation for the "natural" spread of the forward voltages of this group of devices can be written as:

$$\begin{aligned} \Delta V_D(T) &= V_{FH} - V_{FL} \\ &= (A_H - A_L) + (B_H - B_L)T \ . \end{aligned} \tag{B4}$$

Therefore, the assumed linear form for eqs (B2) and (B3) result in a linear equation for $\Delta V_D(T)$, and hence the assumption made earlier is justified.

The two boundary conditions required to evaluate eq (B4) are : 1) the observed spread at liquid nitrogen temperature, $\Delta V_D(-196)$, and 2) the fact that the intercept at -273°C for both V_{FH} and V_{FL} are identical [10], $V_{FH} = V_{FL}$, or $\Delta V_D(-273) = 0$. Hence,

$$\Delta V_D(T) = \frac{\Delta V_D(-196)}{77}[273 + T] \qquad -196°C \leq T \leq -40°C \ . \tag{B5}$$

In the temperature range for V_{F2} [eq (2)], similar reasoning and the application of boundary conditions at 24°C and -273°C yield the following equation:

$$\Delta V_D(T) = \frac{\Delta V_D(24)}{77}[273 + T] \qquad -10°C \leq T \leq 35°C \ . \tag{B6}$$

From figure 12, it can be seen that $\Delta V_D(-196)$ = 2.5 mV and $\Delta V_D(24)$ = 10.0 mV; the slopes calculated from eqs (B5) and (B6) then give 3.25 mV/°C and 3.37 mV/°C, respectively. A straight line through the liquid nitrogen data point (-196°C) with a slope of 3.25 mV/°C would be a reasonable representation for ΔV_D in the range $-196 \leq T \leq -40$°C; the same can be said for a line of slope 3.37 mV/°C through the data point at 24°C. Although coincidental for this case, the slopes of eqs (B5) and (B6) are virtually identical, and hence, either line is a good description for ΔV_D over the entire temperature range of interest.

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This report describes the design and characterization of a variable-temperature wafer apparatus for use in the detection of electrically active defects which produce deep levels in the band gap of silicon. In its present form, the wafer chuck can heat and cool wafers as large as 51 mm in diameter over the temperature range from -196 to 350°C; heating rates as high as 7°C/s have been achieved. The uniformity of the temperature across the chuck under static conditions is estimated to be better than ±0.4°C. Construction details of the chuck are given in an appendix. The use of this apparatus is illustrated by wafer mapping the gold defect density in diodes fabricated across a silicon wafer.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Deep level measurements; defect mapping; hot/cold wafer chuck; thermal wafer chuck; thermally stimulated measurements; wafer chuck, variable temperature.

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